The study of dense matter through jet modification *

A. Majumder

Department of Physics, Duke University, Durham North Carolina, 27708, USA

The use of jet modification to study the properties of dense matter is reviewed. Different sets of jet correlations measurements which may be used to obtain both the space-time and momentum space structure of the produced matter are outlined.

1. Introduction

It is now established that the collision of heavy-ions at the Relativistic Heavy-Ion collider have led to the formation of an entirely new form of matter [1]. While the underlying degrees of freedom prevalent in the hot plasma are, as yet, unknown [2], various constraints may be imposed through a study of its partonic substructure. The foremost tool in this study is the modification of the hard jets, usually referred to as jet quenching [3]. The number of hadrons with transverse momentum $p_T \geq 7$ GeV (which, necessarily originate in the fragmentation of hard jets) is reduced by almost a factor of 5 in central Au-Au collisions, compared to that expected from elementary nucleon nucleon encounters enhanced by the number of expected binary collisions [4].

Jet modification is a probe with a wide range of complexity in terms of experimental observables. By now, measurements on single inclusive observables have been extended to very high p_T ($p_T \leq 20$ GeV). There also exist, a large number of multi-particle jet-like correlation observables, photon-jet, jet-medium and heavy flavor observables [1]. In these proceedings, we attempt a very brief review of the underlying theory and some of the new jet correlation observables which may be used to understand the underlying space-time and momentum space structure of the produced matter.

2. Jet Quenching: theory

Most current calculations of the in-medium modification of light partons may be divided into four major schemes, often referred to by the names of

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the original authors. All schemes utilize a factorized approach, where the final cross section to produce a hadron h with high transverse momentum p_T and a pseudo-rapidity between η and $\eta + d\eta$ may be expressed as an integral over the product of the nuclear structure functions $[G_a^A(x_a), G_b^B(x_b)]$, to produce partons with momentum fractions x_a, x_b, a hard partonic cross section to produce a hard parton with a transverse momentum E and a medium modified fragmentation function for the final hadron $[\tilde{D}^h(p_T/E)]$, The modification of the partonic jet is encoded in the calculation of the medium modified fragmentation function. The four schemes of energy loss are in principle a different set of approximation schemes to estimate this quantity from perturbative QCD calculations.

The reaction operator approach in opacity, often referred to as the Gyulassy-Levai-Vitev (GLV) scheme [5], assumes the medium to be composed of heavy, almost static, colour scattering centers (with Debye screened Yukawa potentials) which are well separated in the sense that the mean free path of a jet $\lambda \gg 1/\mu$, the colour screening length of the medium. The opacity of the medium $\bar{n}$ quantifies the number of scattering centers seen by a jet as it passes through the medium, $i.e.$, $\bar{n} = L/\lambda$, where L is the thickness of the medium. At leading order in opacity, a hard jet, produced locally in such a plasma with a large forward energy $E \gg \mu$, scatters off one such potential and in the process radiates a soft gluon. Multiple such interactions in a Poisson approximation are considered to calculate the probability for the jet to lose a finite amount of its energy.

The path integral in opacity approach, referred to as the Armesto-Salgado-Wiedemann (ASW) approach [6], also assumes a model for the medium as an assembly of Debye screened heavy scattering centers. A hard, almost on shell, parton traversing such a medium will engender multiple transverse scatterings of order $\mu \ll E$. It will in the process split into an outgoing parton and a radiated gluon which will also scatter multiply in the medium. The propagation of the incoming (outgoing) partons as well as that of the radiated gluon in this background colour field may be expressed in terms of effective Green's functions, which are obtained in terms of path integrals over the field. Also similar to the GLV approach, a Poisson approximation is then used to obtain multiple emissions and a finite energy loss.

In the finite temperature field theory scheme referred to as the Arnold-Moore-Yaffe (AMY) approach [7], the energy loss of hard jets is considered in an extended medium in equilibrium at asymptotically high temperature $T \to \infty$ (and as a result $g \to \infty$). In this limit, one uses the effective theory of hard-thermal-loops (HTL) to describe the collective properties of the medium. A hard on-shell parton undergoes soft scatterings with momentum transfers $\sim gT$ off other hard partons in the medium. Such soft scatterings

induce collinear radiation from the parton, with a transverse momentum of the order of gT. Multiple scatterings of the incoming (outgoing) parton and the radiated gluon need to be considered to get the leading order gluon radiation rate. This is obtained from the imaginary parts of infinite order ladder diagrams. These rates are then used to evolve an initial distribution of hard partons through the medium in terms of a Fokker-Plank equation.

In the higher-twist scheme [8], one directly computes the modification to the fragmentation functions due to multiple scattering in the medium by identifying and re-summing a class of higher twist contributions which are enhanced by the length of the medium. The initial hard jet is assumed to be considerably virtual, with $Q \gg \mu$. The propagation and collinear gluon emissions from such a parton are influenced by the multiple scattering in the medium. One assumes that, on exiting the medium, the hard parton has a small, yet perturbative scale q^2. One evolves this scale back up to the hard scale of the original produced parton, Q^2, by including the effect of multiple emissions in the medium. The multiple scatterings introduce a destructive interference for radiation at very forward angles and as such modify the evolution of the fragmentation functions in the medium.

In any scheme, the magnitude of the modification is controlled by a single space-time dependent parameter which may be related to the well known transport coefficient $\hat{q}$. This is defined as the mean transverse momentum squared per unit length, transferred by the medium to the hard jet. In actual computations, a model of the space-time dependence is invoked, and a maximum for $\hat{q}$ is set to best fit with experimental results. Values of the maximum of $\hat{q}$, in the vicinity of the center of a central collision, at a time of $\sim 1\mathrm{fm/c}$, range from 1 GeV^2/fm up to 20 GeV^2/fm [9], depending on the scheme, as well as, the model of the medium used.

3. Jet Correlations

While the suppression of single inclusive hadrons may be used to determine the maximum value of $\hat{q}$, corrrelations between the leading hadron and the medium may be used to test the space-time profile which is used as the ansatz [10]. Once considers the nuclear modification factor R_{AA} as a function of the angle with the reaction plane. The results of such an analysis, from the higher twist approach, for a medium profile taken from a full $3-D$ hydrodynamics simulation at $20-30$ % centrality are presented in the left panel of Fig. 1. The plots clearly demonstrate that the modification is maximal when the jet propagates through the thickest part of the medium in a direction perpendicular to the reaction plane. The spread between the lines is directly dependent on the particular space-time ansatz chosen for the evolution of the produced matter.

To determine the momentum structure of the plasma, one generalizes $\hat{q}$ from a scalar to a tensor [11], where the scalar $\hat{q} = \delta^{ij}\hat{q}_{ij}$. An example where such a situation may arise is in the presence of large turbulent colour fields, which may be generated in the early plasma due to anisotropic parton distributions [12]. These large fields, transverse to the beam, tend to deflect radiated gluons from a transversely traveling jet, preferentially, in the longitudinal directions. While such effects influence the solid angle distributions of the radiated gluons around the originating parton, they do not have a considerable effect on the total energy lost. Such phenomena may yield an explanation for the ridge like structure seen in the near side correlations [11]. In the right panel of Fig. 1, results from a quantitative estimate are presented where the trigger quark (with $E = 10$ GeV) radiates a 4 GeV gluon, which is then subjected to such transverse fields (over a distance of 3 fm). Using a time dependent $\hat{q}$, with an initial value consistent with fits to experiment, one obtains a noticeable ridge like structure, *i.e.*, a considerable broadening in η but not in
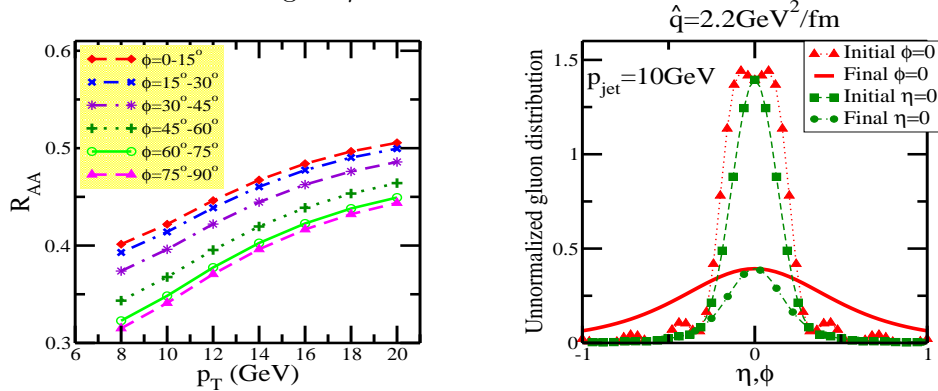

Fig. 1. Left panel: R_{AA} as a function of p_T for different ranges of ϕ the angle to the reaction plane in *Au-Au* collisions at $20 - 30\%$ centrality. Right Panel: The pseudo-rapidity (η, at $\phi = 0$) and azimuthal angle (ϕ, at $\eta = 0$) distribution of 4 GeV gluons radiated from a 10 GeV trigger quark immediately after formation (Initial) and after propagating through 3 fm of turbulent plasma (Final).

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